

Modernization of Vibration Analyzers Based on Identification Measurements

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Abstract—A technology is described for revamping vibration analyzers by introducing an additional intelligent unit for analyzing temporal characteristics of measurement signals. The unit flowchart includes a database, storing expert appraisals, and a knowledgebase, constructed based on the method of identification measurements of the regularity/chaoticity properties in the characteristics of vibration signals using the technique of scales. A computer-aided device has been developed for studying the applicability of the proposed techniques. Results of the vibrodiagnostics of a pumpjack with this device are presented.

Keywords: vibration analyzers, vibrometer, identification measurements, intelligent devices

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INTRODUCTION

Measurement of vibrations is a commonly used process that allows assessment of the state of mechanisms and machinery and diagnostics of faults in equipment. Measuring and analyzing vibration characteristics has become widespread in scientific research related to oil and gas industry and power engineering [1].

Vibration characteristics are measured with vibrometers, which are able to record only integral level of vibration, and vibration analyzers, intended for measuring adjusted levels of vibration accelerations and velocities of the one-octave, one-third-octave, and narrowband spectra of signals from various transducers and for recording the shape of the signals and analyzing them in the time domain.

The analysis makes it possible to determine both the parameters and functional dependences of the input signal represented as functions of time. In the former case, it is the parametric analysis, which offers algorithms for calculating the parameters of the array of instantaneous values of the input signal, for example, its maximum, minimum, average, average rectified, and root-mean-square values over prescribed intervals. The latter trend is the functional analysis, which allows one, based on the array of instantaneous values of the input signal, to derive various functional dependences, for example, correlation and spectral functions of signals. RPE ROS (Perm') [2] and ZETLAB Company (Moscow) [3] are among the leaders in developing and implementing vibration analyzers.

There exist different technologies in vibrometry for digital processing of complex signals. They allow one to conduct in-depth analysis of the signals and require developing sophisticated AI-structured systems of diagnostics and monitoring. These technologies are exemplified by wavelet transforms [4], neural networks [5], and so on. Of special interest is the temporal analysis of complex signals that contain steady- and unsteady-state components with the aim to assess the regularity/chaoticity properties of these signals. This raises an important problem about establishing logical connections between the types of defects and the regularity/chaoticity degree estimates.

The authors propose to use the theory of identification measurements of signals (TIMS) [6] to solve this problem. TIMS is an aggregate of intelligent technologies (means and tools) for the identification, recognition, and digital processing of the shape and variability of signals within the structure of global references. Combining the use of TIMS and the embedding of intelligent instruments into the existing systems of signal recognition and identification has already made it possible to enhance the efficiency of

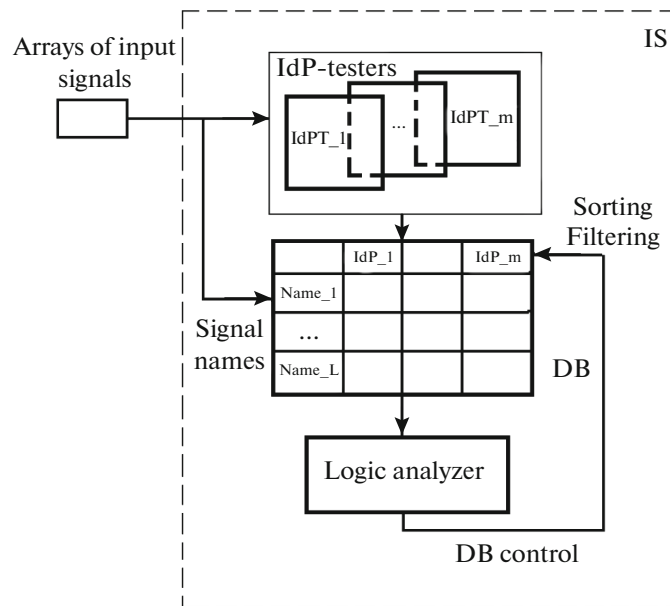


Fig. 1. Flowchart of identification scale.

diagnostics and the accuracy of assessing the condition of fuel cells [7], hydroelectric generators [8], and oil and gas equipment [9].

Extending the existing functional capabilities of vibration analyzers by the possibility for applying the analysis of time-domain characteristics of input signals will apparently significantly increase the efficiency of these devices.

The goal of this paper is to explore the possibility for applying scientific-theoretical notions of the theory of identification measurements of signals to the analysis of temporal characteristics of vibrations, to develop a simple and efficient method for processing of time-domain characteristics, and to propose a new structure for vibration analyzers.

1. ELEMENTS OF THE THEORY OF IDENTIFICATION MEASUREMENTS

TIMS is concerned with measuring the form of the distributions of instantaneous values and the variability as well as the time intervals of a signal and its characteristics with the subsequent processing of identification parameters within the structure of global references using an identification scale (IS). Figure 1 shows an IS structure that incorporates elements that are typical of the state-of-the-art artificial intelligence systems.

Identification IdP-testers are computer-aided tools for converting the arrays of input signal characteristics into identification parameters (IdP-parameters), which can be quantitative values or linguistic characteristics (LCs) that exhibit properties obeying the principles of scale invariance, equivalence, and consistent ordering. The built-in database (DB) stores information on the IdP-parameters, the sorted names of shapes, and the variability of references. IdP-parameters, which are the results of processing for signals from certain object states or the names of signals with distributions that are known from the theory of data-measuring systems, can also serve as the references. The intellectual power of the scale and the resolving ability of recognizing input signals depend on the number of references used.

A logic analyzer (LA) operates based on issuing expert judgements (both quantitative and qualitative) or measurement-process control recommendations from the results of identification measurements of input signal characteristics, applying the methods and algorithms for sorting and filtering references, and comparing the identification parameters of signals with the reference values. The expert appraisals are formed by a specialist expert in the relevant subject area.

A specific feature of the IS is the possibility for measuring the shape and variability of not only temporal but also other (spectral, correlation, wavelet) signal characteristics.

Table 1. Example of scale compilation.

<i>D</i> -Scale	<i>M</i> -Scale	<i>R</i> -Scale
$y = \text{Sort } X \uparrow$	$x(t)$	$z = \text{Sort } x \downarrow$
–3.01	–2.555	–1.89
–2.975	–2.03	–2.03
–2.905	–2.765	–2.1
–2.835	–2.31	–2.31
–2.765	–2.345	–2.345
–2.73	–2.905	–2.485
–2.555	–3.01	–2.555
–2.485	–2.73	–2.73
–2.345	–1.89	–2.765
–2.31	–2.835	–2.835
–2.1	–2.975	–2.905
–2.03	–2.485	–2.975
–1.89	–2.1	–3.01

2. PROCEDURE OF USING TIMS

Procedures for using TIMS may differ, depending on how a particular diagnostics and monitoring problem is posed.

Our research resulted in proposing a method for processing time-domain characteristics of input vibration signal that is based on the techniques of estimating the deviations of the identification parameters of characteristics.

Algorithmically, the method is implemented via the sequence of the following steps.

Step 1. Inputting the temporal characteristic of an input signal $X(t)$; forming the array of distributions of instantaneous values $X(t) \Rightarrow [X_1, \dots, X_N]$ for a given sampling N .

Step 2. Creating the following three scales:

- (1) main (measurement) scale (*M*-Scale) with instantaneous sampled values of signal $X(t)$;
- (2) direct scale (*D*-Scale) with instantaneous values of signal $X(t)$ ranked in ascending order;
- (3) reverse scale (*R*-Scale) with instantaneous values of signal $X(t)$ ranked in descending order.

The second and third scales are ordered and remain constant for the given sampling. The deviation between the two prescribes a range accommodating the measurement scale.

Table 1 provides an example of how these scales are compiled.

Identification measurement consists in scanning the input signal by phase through circular register one-step shifts of the values of the measurement scale (*M*-scale), i.e., the first values travels to the second position, with the first position taken by the last value in the sampling, and so on. This results in the *M*-scale changing its position with respect to the other scales according to the register circular shift.

Step 3. The deviations of the measurement scale with regard to the *D*-Scale and *R*-Scale under input-signal phase scanning are determined using the expressions

$$D = \sum_{i=1}^N |d_i| = \sum_{i=1}^N |y_i - x_i|, \quad (1)$$

$$R = \sum_{i=1}^N |r_i| = \sum_{i=1}^N |z_i - x_i|. \quad (2)$$

The scanning results in two trajectories of measurement-scale movement and, accordingly, in the phase portrait (characteristic) of the signal.

Step 4. The relative distances of trajectories (*D*) and (*R*) are determined. As the *D*-Scale and *R*-Scale are ordered (regular) and oppositely directed, with the *M*-Scale being always in between them, there emerges a possibility for the quantitative estimation of the regularity/chaoticity properties of signals.

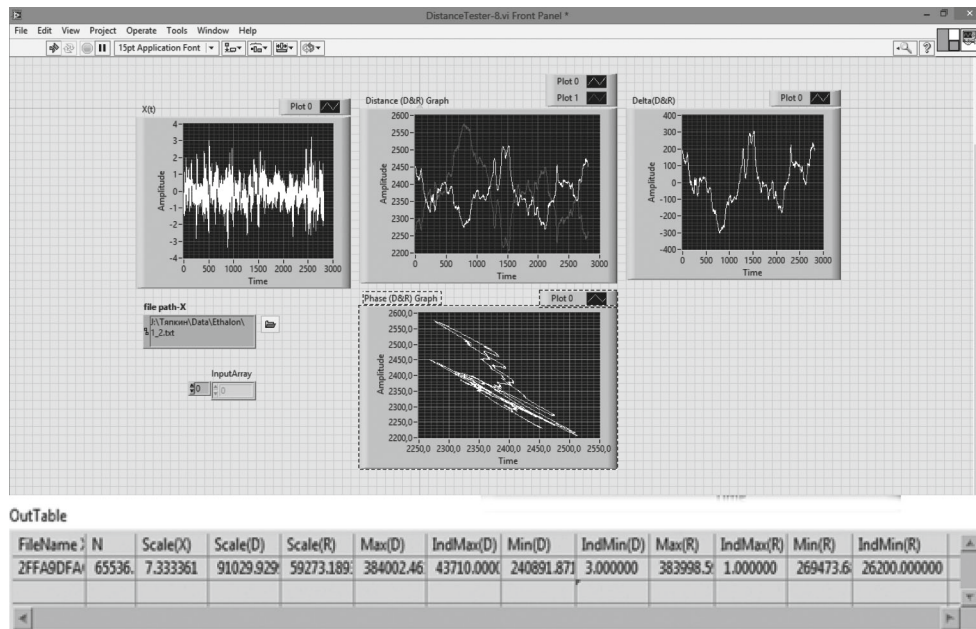


Fig. 2. Front panel of computer-aided device for measuring temporal characteristics.

To investigate the proposed method, a computer-aided device for processing temporal characteristics of complex vibration signals was developed in the LabVIEW environment. The top part of the device front panel (Fig. 2) hosts indicators (monitors) that display the characteristics to be used for analysis and expert judgements, viz.,

- the input signal shape, which is a temporal characteristic of the input signal;
- the changes in the identification parameters D (the while line) and R (the blue line), which are deviations of the measurement scales from the boundaries under input-signal phase scanning;
- the difference between identification parameters D and R ;
- the phase portrait [10] is formed as the union of the differences between the scales, i.e., $\Phi P = \cup(d_i, r_i)$, determined using formulae (1) and (2).

The panel also hosts experiment control elements such as the file location indicator in the device (file path X); a tool for inputting the sample size (Progress); a toggle for outputting experimental results as a separate (Excel) spreadsheet file.

Research conducted with actual diagnostic signals resulted in identification parameters sufficient for describing the state of the tested object. The bottom of the device front panel displays the results of identification measurements in the form of a table (File Name):

- (1) N signal sample size;
- (2) Scale(X) signal size;
- (3) Scale(D) left boundary size (D);
- (4) Scale(R) right boundary size (R);
- (5) Max(D) maximum trajectory deviation (D);
- (6) IndMax(D) coordinate of maximum trajectory deviation (D);
- (7) Min(D) minimum trajectory deviation (D);
- (8) IndMin(D) coordinate of minimum trajectory deviation (D);
- (9) Max(R) maximum trajectory deviation (R);
- (10) IndMax(R) coordinate of maximum trajectory deviation (R);
- (11) Min(R) minimum trajectory deviation (R);
- (12) IndMin(R) coordinate of minimum trajectory deviation (R).

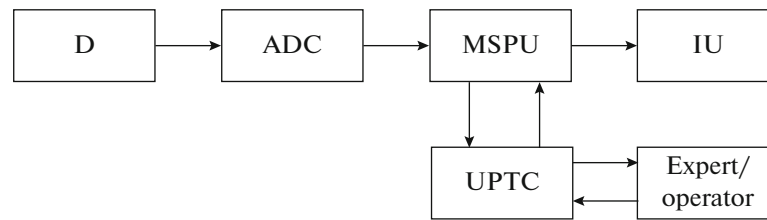


Fig. 3. Flowchart of vibration analyzer equipped with intelligent unit for processing of temporal characteristics.

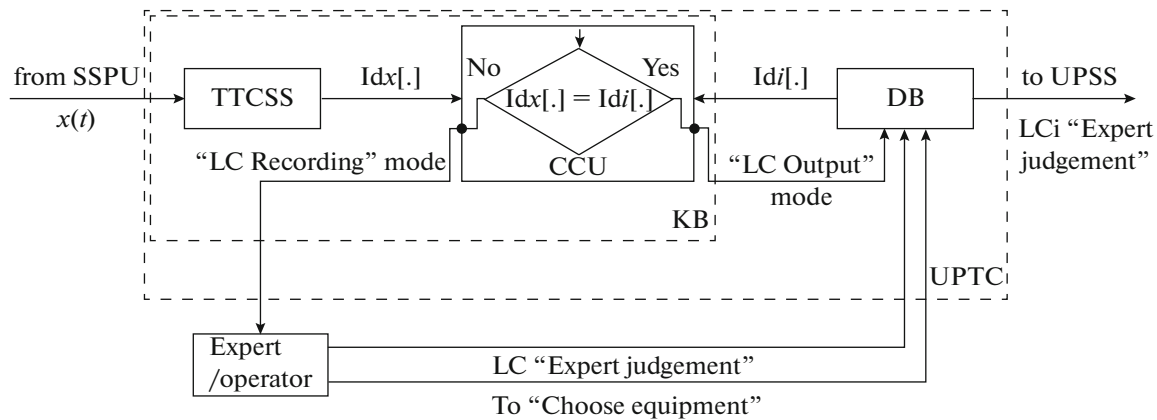


Fig. 4. Flowchart of UPTC.

3. FLOWCHART OF VIBRATION ANALYZER EQUIPPED WITH INTELLIGENT UNIT

A vibration analyzer has been proposed that performs not only traditional parametric and functional analyses but also digital processing of temporal characteristics of measurement signals. The flowchart of the vibration analyzer equipped with the intelligent unit for processing temporal characteristics (UPTC) of measurement signals is shown in Fig. 3.

The figure also includes units that are typical of already existing vibration analyzers such as vibration detector D , analog-to-digital converter ADC, measurement-signal processing unit (MSPU), and indicator unit IU.

Figure 4 shows a UPTC flowchart that illustrates its operation principle. The UPTC functions in two modes (“LC Output” and “LC Recording”) and incorporates a database (DB) and a knowledgebase (KB). An expert operator is a specialist expert in nondestructive testing and evaluation, participating in measurement processes and formulating linguistic assessments and judgements that are stored in the DB.

The DB has a structure that includes quantitative values of the identification parameters $Idi[.]$ of temporal characteristics of measurement signal and respective linguistic expert assessments and judgements (i is the DB row number) (Table 2).

Each test object has its own, individual DB; therefore, the operator forms a “Choose equipment” instruction prior to running a measurement experiment.

According to the procedure developed in the DB, the formed temporal characteristic of the studied signal $X(t)$ from the SSPU output is transmitted to a transformer (TTCSS) for identification measurements that outputs the array of parameters of identification measurements $Idx[.]$.

A cyclic-comparison unit (CCU) performs cyclic comparison of the relevant identification parameters of the studied signal with the ones stored in the DB for every faulty state. If the two are equal, $Idx[.] = Idi[.]$, the UPTC goes into the “LC Output” mode, and experts’ linguistic assessments and judgements are output. Otherwise, the “LC Recording” mode is entered, and, with participation from the expert, linguistic characteristics are formed for $Idx[.]$ and stored in the DB.

Table 2. DB structure

Identification parameters, $Idi[.]$				Expert assessments and judgements	
Scale(X)	Scale(D)	...	IndMin(R)	⟨Designation and name of fault⟩	⟨Recommendations on elimination⟩

Table 3. Expert assessments of faulty states of pumpjacks

State	Defect designation	Defect name
Vibrodiagnostics		
C(1)	SKD.DP.1.0	Defect of bearing in the first electric motor
	SKD.DP.20	Defect of bearing in the second electric motor
C(2)	SKD.OK.3.0	Loosening of attachment of assembly to frame
	SKD.OK.4.0	Loosening of attachment of frame to foundation
	SKD.OK.1	Unfastening at point 1 of electric motor
	SKD.OK.2.0	Unfastening at point 2 of electric motor

4. RESEARCH RESULTS

To investigate the applicability of the technologies proposed in this paper, the designed UPTC was embedded into the small-size Korsar vibration analyzer (RPE ROS, Perm'). Owing to its small dimensions and simplicity of use, this device is currently employed for the **vibrodiagnostics** of pumps of various brands, compressors, turbine units, fans, blowers, smoke exhausters, foundations, transformers, etc. Recorded measurements can be stored in the vibration-analyzer memory or transmitted to a computer via USB or RS-232 interface for further processing by the developed identification-measurement device.

Experimental research was conducted jointly with RPE ROS on in-service pumpjacks. This equipment is intended for imparting translational motion to a deep-well sucker-rod pump located at the bottom of an oil well. To operate efficiently, this equipment needs a unique kinematic configuration and, most importantly, timely in-service diagnostic checks with an "as required" replacement of parts and components.

The diagnostics of pumpjacks is currently performed based on the analysis of spectral frequency characteristics of vibrational diagnostic signals and wattmetergrams (diagnostic measurements of consumed power). Table 3 presents expert judgements for faulty states derived in vibrodiagnostic testing with the Korsar vibrometer.

There are six currently known faults in pumpjacks [2], but the available technique of analysis of frequency characteristics is able to discriminate only faulty states $C(1)$ and $C(2)$, which are groups of faults with similar signs. Hence, if the analysis procedure is able to identify the name of a particular fault that contributes most to the overall vibration level, the accuracy of vibrodiagnostics improves considerably.

As a result of the research, it has been established that

(1) on the average, with a likelihood of 95%, all 6 pumpjack faults can be recognized using vibrodiagnostic signals; therefore, vibration analyzers can be upgraded by applying some elements of TIMS to the analysis of temporal characteristics;

(2) the regularity/chaoticity property of vibration signals can be conveniently measured using the technique of three scales, with two immovable scales (D -Scale, R -Scale) prescribing the range of measurements and the third, measurement scale (M -scale) determining the deviation of phase displacement and its position in the course of scanning with respect to D -Scale and R -Scale;

(3) the degree of regularity/chaoticity is determined based on the relative distance between the measurement M -scale and the two other scales (D -Scale and R -Scale);

(4) a shift of the measurement scale from the center in this or that direction indicates the presence of a certain regularity (orderliness) in the signal, since D -Scale and R -Scale are ranked, respectively, in ascending and descending order of the values of the signal being analyzed;

(5) with a certain likelihood, the presence of a certain regularity (orderliness) in the signal indicates the presence of faults in a tested object;

(6) correspondence between the results of identification measurements of the degree of regularity/chaoticity and the types of possible defects is established by logic analysis, involving the expertise of experts

in a particular subject area, thus implying that this procedure should be individual for every object being analyzed;

(7) intelligent UPTC unit can be fully implemented using modern microcontrollers (for example, STM32) and can be easily embedded in state-of-the-art vibration analyzers, while providing for remote diagnostics and monitoring as well as dispatching control of objects.

CONCLUSIONS

It has been established that the scientific theoretical notions of the theory of identification measurements are fully applicable to the analysis of temporal characteristics of complex vibration signals and ensure sufficiently efficient estimation of the state of dynamic equipment.

The procedure of identification measurements of regularity/chaoticity properties with the use of three scales makes it possible to adequately identify and recognize complex-shaped temporal characteristics of vibration signals.

The proposed vibration analyzer equipped with the intelligent unit for processing of temporal characteristics of vibration signals has a number of merits, as it can additionally supply expert appraisals of the state of equipment.

Further research will be focused on building up the database of vibration analyzers that use identification measurements not only for pumpjacks but also for other industrial equipment.

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